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International Developments in the Field of Unconventional Gas and Oil Extraction

Luca Gandossi

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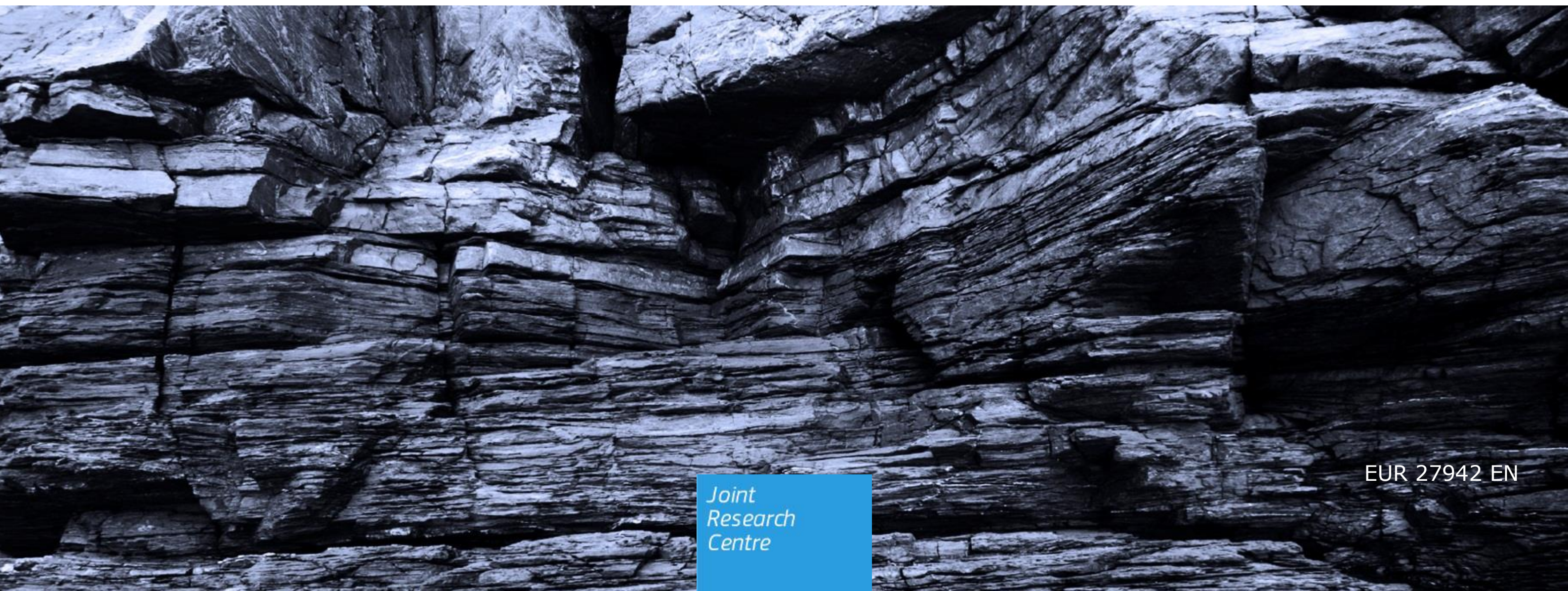

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Abstract

The last few years have witnessed a wealth of studies, reports and assessments being published in many EU member states, by national and international organisations and in the research community on economic, environmental and human health related aspects of unconventional oil and gas exploration and production. Many R&D initiatives are also underway.

This report attempts to provide a survey of several of such studies and initiatives, with a focus on the years 2014, 2015 and early 2016. Principally, reports and studies from public bodies and scientific institutes were covered. Additionally, several papers published in peer-reviewed journals were included.

A review of the quality of the studies covered, the accuracy of their claims and their possible limitations was not carried out. This report is therefore only meant to provide a compilation of their summaries, without any endorsement of the findings reported in any of the studies and assessments covered in the report.

1 Introduction: unconventional hydrocarbons

Globally, fossil fuels supply more than 80% of primary energy (IEA 2015). Conventional and unconventional fossil fuels differ in their geologic locations and accessibility. While conventional fuels are normally found in discrete, easily accessible reservoirs, unconventional fuels may be found within pore spaces throughout a wide geologic formation and require advanced technologies to extract. If unconventional oil resources (e.g. shale oil, oil shale, oil sands-based extra heavy oil and natural bitumen) are taken into account, the global oil technically recoverable reserves quadruple current conventional reserves (World Energy Council 2013).

The following section has been adapted from the factsheet developed by the (Center for Sustainable Systems - University of Michigan 2015). Table 1 summarises the various resources types.

Unconventional natural gas and oil are primarily sourced in three forms: shale gas/oil found in low-permeability shale formations, tight gas/oil found in low-permeability sandstone and carbonate reservoirs, and coalbed methane found in coal seams (NETL 2013).

Although several countries have begun producing unconventional gas, many global resources have yet to be assessed. According to current estimates, China has the largest technically recoverable shale gas resource with 1,115 trillion cubic feet (Tcf), followed by Argentina (802 Tcf) and Algeria (707Tcf) (U.S. Energy Information Administration 2013). Global tight gas resources are estimated at 2,684 Tcf, with the largest in Asia/Pacific and Latin America (International Energy Agency 2012). Resources of coalbed methane are estimated at 1,660 Tcf, with more than 75% in Eastern Europe/Eurasia and Asia/Pacific (International Energy Agency 2012).

Oil sands, i.e., "tar sands" or "natural bitumen," are a combination of sand (83%), bitumen (10%), water (4%), and clay (3%). Bitumen is a semisolid, tar-like mixture of hydrocarbons. Known oil sands deposits exist in 23 countries (World Energy Council 2013). Canada has 73% of global estimated technically recoverable oil sands, approximately 2.4 trillion barrels (bbls) of oil in place.

Deposits less than 75 metres below the surface are mined and processed to separate the bitumen (Ramseur, Lattanzio et al. 2014). Bitumen must be upgraded to synthetic crude oil before refining into petroleum products; non-upgraded bitumen must be diluted or mixed with synthetic crude oil before transport. Deeper deposits employ in situ (underground) methods, including steam or solvent injection, or oxygen injection with a portion of oil sands burned for heat. Cyclic steam stimulation and steam-assisted gravity drainage are common in situ methods.

Oil shales are sedimentary rocks containing deposits of organic compounds (kerogen) which have not undergone enough geologic pressure, heat, and time to become conventional oil. Oil shale contains enough oil to burn without additional processing, but can be heated (retorted) to generate petroleum-like liquids (RAND Corporation 2005). Known oil shale deposits exist in 40 countries. The U.S. has the largest oil shale technically recoverable resource in the world, approximately 3.7 trillion barrels of oil in place (77% of world supply), of which the Green River formation in the Western U.S. accounts for 83% (U.S. Energy Information Administration 2015).

Oil shale can be processed in two ways. In the first method, the oil shale is mined and brought to the surface to be retorted to temperatures around 500°C.The second method, in situ conversion process, involves placing electric heaters throughout the shale for up to three years until the rock is heated up to 340-370°C, at which point oil is released (Andrews 2008). Oil retorted above-ground must be further processed before refining and the spent shale disposed. Oil extracted through in situ conversion can be sent directly to the refinery.

Table 1 Identification of resources types and sub-categories

<table>
<tr><th></th><th>Resources type</th><th>Description</th><th>Resource sub-category</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Unconventional Natural Gas/Oil</td><td rowspan="3">Natural gas or oil trapped in unconventional reservoir rocks (tight sands, shales, coal beds, etc.)</td><td>Shale gas/oil from low-permeability shale formations</td></tr>
<tr><td>Tight gas/oil from low-permeability sandstone and carbonate reservoirs</td></tr>
<tr><td>Coal bed methane from coal seams</td></tr>
<tr><td>2</td><td>Tar Sands (also Oil Sands or Natural Bitumen)</td><td>Combination of sand, bitumen, water and clay. Bitumen is a semisolid, tar-like mixture of hydrocarbons.</td><td>Tar Sands</td></tr>
<tr><td>3</td><td>Oil Shales</td><td>Sedimentary rock that holds deposits of organic compounds (kerogen) that have not undergone enough geologic pressure, heat, and time to become conventional oil. <u>Not to be confused with shale oil</u>.</td><td>Oil Shales</td></tr>
<tr><td>4</td><td>Methane Hydrates (also Methane Clathrates)</td><td>Solid compounds where a large amount of methane is trapped within a crystal structure of water, forming solids similar to ice.</td><td>Methane Hydrates</td></tr>
</table>

Methane hydrates are ice-like combinations of gas and water that form naturally and in great quantities. Water molecules, which make up approximately 85 per cent of a gas hydrate, form a crystalline lattice. The lattice is stabilized by other molecules, usually methane. Methane gas hydrates form naturally where adequate supplies of methane and water can combine in a location with both high pressure and relatively low temperature, typically in the Arctic (where cold air temperatures create thick zones of permanently frozen soils) and at the bottom of oceans or deep inland lakes. The methane itself is created by the decomposition of organic carbon, which generally migrates upward through water-laden sediment. In the right conditions, this triggers the formation of gas hydrates (Beaudoin 2015).

Most marine gas hydrate deposits found so far have been in continental margin and slope sediments. The global inventory of gas hydrates appears to be very large. Recent technically recoverable estimates of the total amount of methane contained in the world's gas hydrates range from 1500 to 15,000 gigatonnes of carbon. At standard temperature and pressure, this represents 3000 to 30,000 trillion cubic meters (Beaudoin 2015).

Experimental programmes have shown that gas hydrates can be produced in the short term using conventional hydrocarbon recovery methods, but it is still too early to conclude whether large-scale methane production from gas hydrates can be carried out economically. (Beaudoin 2015) conclude that meaningful production of methane from gas hydrates is probably still a decade or more away in the future.

The last few years have witnessed a wealth of studies, reports and assessments being published in many EU member states, as well as by national and international organisations and in the research community, covering economic, environmental and public health aspects related to the exploitation of unconventional hydrocarbons. Many R&D initiatives are also currently underway. This report attempts to provide a survey of several of such studies and initiatives, with a focus on shale gas and mainly covering the years 2014, 2015 and early 2016. Some earlier reports (not older than 2011) are covered as well. Principally, reports and studies from public bodies and scientific institutes were covered. Additionally, relevant papers published in peer-reviewed journals were included.

Each study or report is briefly described and a selection of its conclusions and/or recommendations is extracted and reproduced herein, but a review of the quality of the studies covered, the accuracy of their claims and their possible limitations was beyond the scope of this report. Therefore, this report is only meant to provide a compilation of such studies and their summaries, without any endorsement of the findings reported.

2 General reports and studies

2.1 Studies on Hydraulic Fracturing

2.1.1 European Academies' Science Advisory Council (2014)

The European Academies' Science Advisory Council published in 2014 a statement which addressed three specific concerns that are being put forward in the public debate about the exploitation of Europe's shale gas potential: (1) the implications of a high population density throughout Europe (in combination with the problem of water usage); (2) the question of methane leakage; and (3) the challenge of (local) public acceptance. The statement found that although these concerns are justified in general, all three of them can be mitigated by use of best practices and proper regulation. The statement thus concluded that the issues considered need to be carefully reflected by policy-makers, but that they are not an unsurmountable obstacle for exploring and using Europe's shale gas potential. It also concluded that the scale of the shale gas resources and the economic viability of its extraction in EU countries remain currently uncertain and that, without exploratory drilling, this uncertainty is bound to continue (European Academies' Science Advisory Council 2014).

2.1.2 The Scottish Government's Expert Scientific Panel (2014)

In September 2013, the Scottish Government convened an Independent Expert Scientific Panel to report on the scientific evidence relating to unconventional oil and gas. The remit of the Panel was to deliver well-researched evidence relating to unconventional oil and gas upon which the Scottish Government can reliably base future policy in this area, an analysis of the environmental and regulatory issues associated with the potential development of unconventional oil & gas in Scotland and an assessment of the potential resources available to Scotland. The results of such work were summarized in a report published in 2014 (The Scottish Government - Independent Expert Scientific Panel 2014).

A selection of the key findings of this study is as follows:

- There could be positive economic impacts from the development of an unconventional oil & gas industry, in terms of jobs created, taxes paid and gross value added, but the scale of the impact in Scotland is subject to debate and may only become clear once development is underway.
- Scotland's geology suggests that there could be significant reserves of unconventional oil and gas, with the greatest potential reserves likely to be in the Midland Valley of Scotland;
- When viewed in the context of the factors that have supported coal bed methane and shale gas development in other countries, it seems likely that unconventional gas could be developed in Scotland at scale. This is particularly true, given Scotland's domestic oil and gas supply-chain industry, and Scotland's longstanding experience in other extractive industries such as coal mining, shale oil, and conventional oil and gas;
- There are a number of technical challenges associated with unconventional hydrocarbon extraction, but none are judged to be insurmountable. The technology exists to allow the safe extraction of such reserves, subject to robust regulation being in place;
- The regulatory framework is largely in place to control the potential environmental impacts of the production of unconventional oil and gas in Scotland, although there may be gaps to address;

- The high population density of those parts of Scotland most likely to host significant unconventional oil and gas resources would be a challenge for any form of reindustrialisation, and will thus be so for any future unconventional oil and gas industry;
- The development of any new industry is likely to impact society. Detecting and alleviating negative impacts and enhancing positive impacts is complicated unless careful planning of how to identify impacts is undertaken;
- Public concerns around unconventional oil and gas development include concerns about technical risk such as water contamination, public health and seismicity, but also wider issues such as social impacts on communities, effect on climate targets and trust in operators, regulators and policymakers;
- Many of these social and environmental impacts can be mitigated if they are carefully considered at the planning application stage. Added to which, there are already considerable legislative safeguards to ensure such impacts are not realised. Early consultation with communities is vital to identify potential impacts on the community, to scope potential benefits and develop plans to mitigate the impacts and enhance the benefits;
- Public engagement is necessary for the development of unconventional oil and gas resources in Scotland and there is a growing body of evidence showing that sustained and meaningful community engagement has beneficial outcomes for communities, operators and policymakers.

2.1.3 Public Health England (2014)

Public Health England (PHE), an executive agency of the UK Department of Health reviewed in 2014 the potential public health impact of direct emissions of chemicals and radioactive material from the extraction of shale gas. Other considerations such as climate change and greenhouse gas emissions, sustainable use of water resources, nuisance issues (noise, traffic, visual impact) and occupational health were not considered in this review, as well as the potential socioeconomic impacts of shale gas extraction (Public Health England 2014). The review focused on the potential public health impacts of exposures to chemical and radiological pollutants as a result of shale gas extraction in the UK, based on the examination of literature and data from countries which already have commercial-scale shale gas extraction operations.

A selection of the key findings of this study is as follows:

- An assessment of the currently available evidence indicates that the potential risks to public health from exposure to the emissions associated with shale gas extraction will be low if the operations are properly run and regulated.
- Most evidence suggests that contamination of groundwater, if it occurs, is most likely to be caused by leakage through the vertical borehole. Contamination of groundwater from the underground hydraulic fracturing process itself (ie the fracturing of the shale) is unlikely. However, surface spills of hydraulic fracturing fluids or wastewater may affect groundwater, and emissions to air also have the potential to impact on health.
- Where potential risks have been identified in the literature, the reported problems are typically a result of operational failure and a poor regulatory environment. Therefore, good on-site management and appropriate regulation of all aspects including exploratory drilling, gas capture, use and storage of hydraulic fracturing fluid, and post-operations decommissioning are essential to minimise the risk to the environment and public health.
- A few of the reviewed studies suggested associations between adverse health impacts and shale gas extraction activities; however, the authors highlighted study limitations and it is evident that further work is required.

- The report made a number of recommendations, for instance stressing the importance of baseline environmental monitoring, of effective environmental monitoring in the proximity of shale gas extraction sites throughout the lifetime of the project, of ensuring that the chemicals used in the fracturing fluid be publicly disclosed and risk assessed prior to use, of characterizing potentially mobilised natural contaminants, including naturally occurring radioactive materials (NORM) and dissolved minerals

2.1.4 Council of Canadian Academies (2014)

The Council of Canadian Academies was tasked by the federal Minister of Environment to assess the state of knowledge about the impacts of shale gas exploration, extraction, and development in Canada. The Council formed a multidisciplinary panel of experts from Canada and the United States to conduct an evidence-based assessment supported by relevant and credible peer reviewed research.

The panel produced a report (The Council of Canadian Academies 2014) which did not include recommendations, but was aimed at informing both the public discussion and a future environmental research agenda on a natural resource that could play an important role in the future of several provinces. An interesting conclusion was the identification of the following five distinct elements to establish an effective framework for managing the risks posed by shale gas development.

1. *Technologies to develop and produce shale gas*. Equipment and products must be adequately designed, installed in compliance with specifications, and tested and maintained for reliability.
2. *Management systems to control the risks to the environment and public health*. The safety management of equipment and processes associated with the development and operation of shale gas sites must be comprehensive and rigorous.
3. *An effective regulatory system*. Rules to govern the development of shale gas must be based on appropriate science-driven, outcome-based regulations with strong performance monitoring, inspection, and enforcement.
4. *Regional planning*. To address cumulative impacts, drilling and development plans must reflect local and regional environmental conditions, including existing land uses and environmental risks. Some areas may not be suitable for development with current technology, whereas others may require specific management measures.
5. *Engagement of local citizens and stakeholders*. Public engagement is necessary not only to inform local residents of development, but to receive their input on what values need to be protected, to reflect their concerns, and to earn their trust. Environmental data should be transparent and available to all stakeholders.

2.1.5 Royal Society of Edinburgh (2015)

The Royal Society of Edinburgh (RSE) published in 2015 a report that looks into options for Scotland's gas future. The report followed a Scottish Government announcement in January 2015 of a temporary moratorium on unconventional gas development, including the use of fracking, to allow for a national debate (The Royal Society of Edinburgh 2015).

The report provides an overview of the options available to Scotland in order to meet its demand for gas over the coming decades. Scotland is heavily reliant on gas in both the residential and commercial sectors for heating. Natural gas also plays a significant role in electricity generation. Even considering an unprecedented decrease in UK gas consumption, a significant quantity would still be required not only for heating, but also as a chemical feedstock for the petrochemical industry.

Two main conclusions were drawn. The first relates to the considerable degree of uncertainty surrounding much of the debate. A reduction in this uncertainty, particularly in relation to onshore and offshore resources and reserves, would enable the decision-making process to be better informed. The Scottish Government is hence urged to consider investing funds to reduce the areas of larger uncertainty, most notably (1) health impacts and (2) potential reserves.

The second relates to the involvement of civil society. The reports notes that the importance of giving the public a genuine opportunity to contribute to the decision-making process regarding decisions over Scotland's gas future. The choice should not be imposed on the public from above, nor should it be left to communities to decide whether they wish to host onshore developments on a case by case basis. The proposed way forward must be addressed at a societal level with meaningful public involvement.

2.1.6 German Academy of Science and Engineering (2015)

The German Academy of Science and Engineering (Deutsche Akademie der Technikwissenschaften - acatech) published a study (in German only) that looks at the technology of hydraulic fracturing and its potential, opportunities and risks, intended for both decision-makers and the interested public.

The most notable conclusion from this report is that a general prohibition of hydraulic fracturing cannot be justified on the basis of scientific and technical facts, provided that the development of unconventional gas (and geothermal energy) follows strict safety standards, is clearly regulated and comprehensively monitored (ACATECH – Deutsche Akademie der Technikwissenschaften 2015).

2.1.7 Basque Institute of Competitiveness (2016)

The Basque Institute of Competitiveness published in 2016 a book with a review of issues related to shale gas and hydraulic fracturing (Álvarez Pelegry and Suárez Diez 2016). The book is written in Spanish.

The book discusses the role of natural gas in the global context, by examining gas demands and production. It examines global resources and reserves, and focus on the situation in Spain and in particular in the Basque country, with an eye on infrastructure as well.

It presents an overview of hydraulic fracturing and related technologies for exploiting shale gas (including topics such as well integrity, horizontal drilling, well completion, circulating and fracturing fluids, etc.). It discusses environmental issues related to fracturing, in particular looking at the water cycle and induced seismicity. Finally, it reviews regulatory and licensing issues.

2.2 European Commission studies on the environmental aspects of unconventional fossil fuels

2.2.1 Study on the application of Recommendation 2014/70/EU (February 2016)

In January 2014, the European Commission adopted a Recommendation setting out minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing (HVHF)[1] (European Commission 2014). The effectiveness of the Recommendation was set for a review by the Commission 18

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[1] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014H0070

months after its publication. The European Commission funded a study, produced by external consultants, to support such review (Ricardo Energy & Environment and Milieu - Law and Policy Consulting 2015).

At present, based on available information, there is no on-going commercial production of hydrocarbons using HVHF in the EU. However, the following Member States have granted or plan to grant authorisations for the exploration or production of hydrocarbons (such as shale gas) that may require the use of HVHF, namely: Austria, Denmark, Germany, Hungary, Lithuania, Netherlands, Poland, Portugal, Romania, Spain, and the United Kingdom (UK). The review evaluated the Recommendation's effectiveness by (1) assessing how Member States apply the principles of the Recommendation and selected EU legal requirements at the planning, licensing and permitting levels, (2) describing regulatory and non-regulatory developments in Member States after the adoption of the Recommendation and (3) gathering stakeholders' views. In addition, it attempted to collect information on the possible cost of the measures taken as a result of the adoption of the Recommendation.

2.2.2 Study on the management of environmental impacts and risks of other unconventional hydrocarbons (September 2015)

The European Commission funded a study, produced by external consultants, to identify and assess relevant measures for managing the risks resulting from unconventional fossil fuels developments other than shale gas (i.e. tight gas, tight oil, coal bed methane) (AMEC 2015).

From a regulatory point of view, a clear definition to differentiate conventional fossil fuels and unconventional fossil fuels would be beneficial. The study concluded that a universally recognised distinction is not available. What is considered to be an unconventional resource may vary over time depending on many aspects (e.g. resource characteristics, available technologies, scale, frequency and duration of production, etc.). Potential options for categorisation are suggested to be based on the following criteria: (1) the permeability of the reservoir formation; (2) the volume of water used in hydraulic fracturing (for shale gas, tight oil and tight gas); (3) the pressure applied during hydraulic fracturing; (4) the depth of the reservoir, due to differences in risks presented by shallower operations (proximity to aquifers) and deeper operations (stricter well integrity requirements); (6) the volume of pumped groundwater (for coal bed methane, CBM).

The report also looked at the differences between risks and impacts resulting from the extraction of such unconventional hydrocarbons, compared to those resulting from shale gas operations. These were predominantly identified in the hydraulic fracturing, well completion and production stages, with CBM being more markedly different than the other types of unconventional fossil fuels. For tight gas and tight oil, risks and impacts linked to water resource depletion were deemed potentially less significant than for shale gas because the reduced amount of water typically required for the fracturing process. Similarly, risks and impacts associated with CBM relating to traffic and air pollution during site identification and preparation, and the well design drilling, casing and cementing stage were judged as entailing potentially lower risks due to the smaller scale and duration of operations and shallower well depths and distances resulting in shorter drilling times. However, for CBM, the hydraulic fracturing stage risks and impacts associated with groundwater contamination were judged potentially more significant compared to shale gas due to the comparatively shallower depth of the target formation.

Additional risks identified for CBM compared to shale gas were identified including a risk of surface water contamination from greater quantities of actively pumped produced water at the surface which must be managed and treated. Finally, risks of increased water resource depletion from groundwater supplies and the potential for groundwater contamination were deemed possible for CBM.

2.2.3 Study on the need for a risk management framework for unconventional gas extraction (August 2014)

The European Commission funded a study, produced by external consultants, aimed at providing an overview on the issues associated with unconventional gas extraction that uses high volume hydraulic fracturing and horizontal drilling (such as shale gas) from an environmental and regulatory perspective; to give an assessment of available measures to address environmental risks and their impacts; and to describe selected policy options available to implement such measures (AMEC 2014).

Beside summarising the key environmental concerns, the study proceeded to identify relevant issues related to EU environmental law. The report for instance concludes that although there are relevant requirements across EU law (the "*acquis communautaire*"), these are not in sufficient detail or specific enough to address all risks arising from unconventional gas exploration and production. Permits obtained under the Mining Waste Directive are limited in their capacity to address all aspects of unconventional gas operations. According to the authors, the *acquis* does not fully address the underground environment, geological, hydrogeological and induced seismicity aspects of unconventional gas extraction.

Also at the Member State level the authors identified legal uncertainties. None of the Member States examined had a regulatory regime specifically addressing unconventional gas. Requirements at national level were found to be not only different but sometimes contradictory. A divergence was highlighted in the regulation of unconventional gas extraction in Member States and also divergence in the interpretation of EU environmental law to address the challenges placed on regulators.

Regarding best practice and voluntary actions by the industry, the authors found that whilst such practices are emerging, they are not well established or fully integrated, particularly taking into account the early stage in development of certain unconventional gas resources such as shale gas in Europe.

The report concluded that a coherent and comprehensive approach is absent at EU level, in particular with regard to strategic planning, environmental impact assessment, integrated baseline reporting and monitoring requirements, capture of gases, well integrity and public disclosure of chemicals.

2.2.4 Study on the mitigation of climate impacts of possible future shale gas extraction in the EU (January 2014)

The European Commission funded a study, produced by external consultants, to follow up on the AEA 2012 study "Climate impact of potential shale gas production in the EU" (AEA 2012b). The objective of this second study was to develop a list of possible policy options for minimizing greenhouse gas emissions during exploration and production of shale gas in the EU, and to assess climate, environmental, social and economic impacts of selected options (ICF International 2014).

More specifically, the goals of the study were to analyse international experiences in minimising on-site fugitive GHG emissions to identify lessons and best practices; to provide an overview of the most advanced technologies and practices that could be promoted or enforced for minimizing these emissions; to provide an overview of different policy options for a possible regulatory framework for minimizing these emissions and to analyse the climate, environmental and economic impacts of key policy options.

3 Resource assessments

3.1 European Union

Shale gas resources in Europe are still uncertain to a large degree, since there has been very limited exploration and no production. The European Commission, via the Joint Research Centre, is funding an ongoing project, called EUOGA and carried out by EuroGeoSurveys (EGS), with the aim to develop a consistent pan-EU data sets and uniform estimation principles.

EUOGA (i.e. "European Unconventional oil and gas assessment") is an inventory of existing published knowledge on shale oil and gas resources in Europe. The project intends to compile data from European countries which are members of EGS and the European Union, including Switzerland and Ukraine.

The work is organised in several subsequent tasks, namely:

1. Define and setup a common resource assessment methodology.
2. Overview of the current status of the exploration and development of shale gas and shale oil in Europe.
3. Geological resource analysis including compilation of geological maps and characteristics of prospective European oil and gas bearing shale formations.
4. Quantitative resource estimation of prospective shale gas and shale oil resources in Europe based on the common assessment methodology.
5. Data and results presentation in a web-interactive database and map application

The resource assessment is performed using basins and plays as main Units of Assessments. The novel methodology allows resource calculation on aggregated (geographical regions, trans-boundary basins) or disaggregated scales (country specific). The resource for all EUOGA Units of Assessments is formulated as theoretical resource while for some individual Units of Assessments total recoverable resource (TRR) is forwarded depending on the availability of detailed information.

Since the project start (third quarter of 2015), EUOGA produced an up-to-date overview of the current status and development of shale gas and oil in Europe, based on a questionnaire sent to all involved National Geological Surveys (including Ukraine and Norway), and a draft report on the development of the common resource assessment methodology. In summary, the currently available information shows that from a total of twenty-six countries covered in this study, twenty-two have a potential resource within their country. In nineteen countries an assessments of the unconventional resources have been performed either by the NGS or a third party, however, not all assessments are publically available. The level of activities in the European member states is generally low and fifteen countries have no present activities and no near future activities are expected. Out of the remaining eleven countries, only six expects future activities. The activity level is in many countries related to the political acceptability and shale hydrocarbon exploration and development is presently only permitted in six countries. A low political support is in most cases described as concerns related to the use of hydro fracturing and the environmental impact.

The preliminary prerequisites for the selected common resource assessment method were chosen as follows:

- Focus of the study is on gas/oil initially in place calculation.
- Identify, address and visualize uncertainty on different scales.
- Resolve data comparability issues due to larger data heterogeneity, between the different basins but also within individual basins.
- Allow the upscale of the calculated gas/oil initially in place values to total recoverable resource estimates.

3.2 EIA: World Shale Resource Assessments

The U.S. Energy Information Administration (EIA) maintains and regularly updates a series of assessments on the world's shale resources[2]. The first edition of the series was released in 2011 and updates are released on an on-going basis. Four countries were added in 2014: Chad, Kazakhstan, Oman and the United Arab Emirates (UAE). A round of updates was published in September 2015.

3.3 Canada

The Canadian Society for Unconventional Resources[3] (CSUR), published in 2015 the 4th edition of the Unconventional Resource Guidebook, including information related to shale gas, tight oil and other unconventional resources in Canada (CSUR 2015).

The Canadian Association of Petroleum Producers[4] (CAPP) and the Canadian Energy Research Institute (CERI) frequently publish[5] relevant report on oil and gas developments, often including unconventional sources.

3.4 Poland's assessment of undiscovered tight gas resources

The Polish Geological Survey carried out in 2014 an assessment of undiscovered tight gas resources in selected tight reservoirs of Poland. Tight gas is produced using similar technologies as in the case of shale gas but present in other types of reservoir rocks (mainly tight impermeable sandstones). The report (Wojcicki; A., Kiersnowski; H. et al. 2014) did not cover tight gas fields recently discovered in reservoir traps in Poland (e.g., Siekierki- Trzek and Pniewy gas fields) but focused on yet unexplored tight gas reservoirs in hydrocarbon basin centers of likely higher potential.

The most probable value of the undiscovered (risked) GIP in the selected reservoirs was assessed to be in the range of 53.94 to 70.42 Tcf. The estimation of technically recoverable resources was also calculated assuming a recovery ratio of 5-15% of the GIP.

3.5 UNEP report on Methane Hydrates

The United Nations Environment Programme (UNEP) published in 2014 a report on methane hydrates, covering all relevant issues in current global gas hydrate research and development (Beaudoin 2015). The report is a two-part review that covers the role of gas hydrates in natural systems (Volume 1) and the potential impact of gas hydrates as a possible new and global energy resource (Volume 2).

Volume 1 is divided into three chapters. As a basis for understanding how gas hydrates occur and evolve in nature, Chapter 1 describes the crystal structures of gas hydrates, their stability requirements, and the environmental settings in which gas hydrates commonly occur. It also gives estimates of the global quantity and distribution of gas hydrates. Chapter 2 summarizes how methane is generated, moved into and out of gas hydrates, and gets consumed. Chapter 2 also discusses the link between gas hydrates and deep marine ecosystems. Chapter 3 considers models of past climate change and future climate conditions and how those models might be affected by potential feedbacks from gas hydrates.

Volume 2 presents the central message that gas hydrates may represent both an enormous potential energy resource and a source of greenhouse gas emissions for a world with ever-increasing energy demands and rising carbon emissions. Even if no

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2 https://www.eia.gov/analysis/studies/worldshalegas
3 http://www.csur.com
4 http://www.capp.ca
5 http://www.ceri.ca

more than a small subset of the global resource is accessible through existing technologies, that portion still represents a very large quantity of gas. To date, a few short-term, pilot-scale methane production tests have been conducted in research wells. The results suggest that larger-scale exploitation may be feasible, but no commercial gas hydrate production has yet occurred. Several nations, however, are currently researching the energy potential of gas hydrates. Recent detailed assessments of the energy potential of methane-gas hydrates concluded that there are no anticipated technical roadblocks to producing gas from hydrate deposits. Ultimately, a combination of technological advances and favourable global/regional market conditions could make gas hydrate production economically viable. Therefore, the second part of the assessment provides a summary of gas-hydrate-based, energy-related information useful in evaluating future energy resource options. Topics addressed include a review of likely future trends in energy supply, a characterization of prospective gas hydrate resources, technologies for exploration and development, and the potential environmental, economic, and social implications of gas hydrate production.

The report mentions that "*science has yet to understand fully the socio-ecological impacts of extracting gas hydrates*". Among the environmental topics requiring further study are featured notably the "*potential ground subsidence associated with production [as gas hydrates are generally located at shallower depths than most currently producing gas reservoirs] and the "disposal of produced water*". Further "*each proposed development must also consider disruption of sensitive ecosystems and the cumulative impact of development on the global climate system*".

4 Economy and Manufacturing Assessments

4.1 World Energy Council study (2016)

The World Energy Council has very recently published a report exploring how the onset of unconventional gas supplies, led by the north American experience, has contributed to the structural shifts currently underway in global natural gas markets (World Energy Council 2016).

An earlier study (World Energy Council 2012) had predicted that shale gas development would have a significant impact on the dynamics and prices of future natural gas markets. In the 2016 study, the World Energy Council explores three significant trends of growing unconventional gas supplies on global markets: (1) interconnected markets, (2) international growth of unconventional gas, and (3) shifting portfolio allocations. The paper explores each of them and draws conclusions regarding the future of natural gas at a global level.

4.2 Hausman & Kellogg study (2015)

Catherine Hausman of the Ford School of Public Policy at the University of Michigan and Ryan Kellogg of the Department of Economics at the University of Michigan and the National Bureau of Economic Research (NBER) examined in 2015 the effects of the US gas supply boom on economic welfare and distributional impacts (Hausman and Kellogg 2015).

The authors provided first new estimates of supply and demand elasticities, which were used to estimate the drop in natural gas prices, and calculated large, positive welfare impacts for four broad sectors of gas consumption (residential, commercial, industrial, and electric power), and a negative impact for producers, with variation across regions. Overall, they found that the shale gas revolution has led to an increase in welfare for natural gas consumers and producers of $48 billion per year, but also noted that more data are needed on the extent and valuation of the environmental costs of shale gas production.

Because natural gas is an important direct input in chemical and cement manufacturing, and is also an indirect input to essentially all manufacturing via its use in electricity generation, Hausman and Kellogg examined the shale gas impact on manufacturing overall, an industry that had been in decline in the US for decades. While they noted that it is difficult to pinpoint a precise causal effect, they found that gas-intensive manufacturing has indeed experienced an expansion of activity as a result of the shale boom, with the most pronounced effect in fertilizer manufacturing.

Hausman and Kellogg conclude by raising an issue currently facing US policymakers: whether to permit large-scale overseas export of liquefied natural gas (LNG). They concluded that expanding natural gas exports will drive up US gas prices, thus reducing consumer surplus but increasing producer surplus, with the gains to producers outweighing the losses suffered by consumers.

4.3 U.S. EIA Productivity Report

The U.S. Energy Information Administration (EIA) collects, analyses, and disseminates energy information to "*promote sound policymaking, efficient markets, and public understanding of energy*". The agency regularly publishes reports on productivity of the most important tight oil and shale gas plays in the US. The latest update was released in April 2016, covering seven regions (Bakken, Eagle Ford, Haynesville, Marcellus, Niobrara, Permian, Utica) that accounted for 92% of domestic oil production growth and all domestic natural gas production growth during the period 2011-14 (U.S. Energy Information Administration 2016).

This report used recent data on the total number of drilling rigs in operation along with estimates of drilling productivity and estimated changes in production from existing oil and natural gas wells to provide estimated changes in oil and natural gas production. The approach did not distinguish between oil-directed rigs and gas-directed rigs because once a well is completed it may produce both oil and gas, and indeed more than half of the wells produce both.

4.4 European Commission study on the macro-economic effects of shale gas extraction in the EU

The European Commission funded a study, produced by external consultants, to assess the impacts of different environmental risk management policies for shale gas on the energy system and the economy. More specifically, the study explored the macro-economic impacts of shale gas development under a base case scenario as well as two alternative policy scenarios to manage environmental risks (Mathis, Hugman et al. 2014).

5 Environmental Assessments

5.1 General Reports

5.1.1 Polish Geological Institute (2015)

A site specific environmental assessment was commissioned by the Polish ministry of the environment and carried out by a consortium led by the Polish Geological Institute and including the University of Science and Technology in Cracow and Gdańsk University of Technology. The aim of the project was to determine the environmental impact of works related to the exploration and appraisal of unconventional hydrocarbon accumulations at 7 test sites, including a detailed analysis of the potential and actual impacts on particular environmental topics, including the following: air, ground surface, soil, surface water and the groundwater. The final report was published in 2015 (Konieczyńska, Adamczak et al. 2015), along with several reports from the research activities at the different individual test sites. The work was also accompanied by a study on seismic monitoring (see Section 5.6.1) and followed a previous environmental study carried out in 2011 at the Łebień site (Polish Geological Institute – National Research Institute 2011).

Initially 5 test sites around the following exploratory wells were chosen: Lubocino-2H, Stare Miasto-1K, Wysin-1, Syczyn OU-2K and Zwierzyniec-1. During the project, the research was expanded to include the test site around Gapowo B-1A exploratory well, as well as research included in the long-term monitoring in the following test sites: Stare Miasto, Syczyn and Zawada, and around Łebień LE-2H exploratory well. In total, a diverse range of works was delivered under the project in the area of 7 test sites, located in the Pomeranian Voivodeship and Lubelskie Voivodeship.

The research covered the following elements: (1) identification of the local conditions and field studies planning, (2) examination of the baseline status of the environment prior to the commencement of exploration, (3) monitoring while drilling vertical/directional wells, (4) monitoring during hydraulic fracture stimulation and gas flow testing, (5) monitoring of the status of the environment on completion of drill site operations, (6) occasional monitoring of the status of the environment at certain times after the completion of downhole operations. It must be noted that for two sites only (out of the seven) it was possible to carry out the assessment of the status of the environment prior to drilling activities and in one case only it was possible to assess the status of the environment after well abandonment. The maximum duration of the monitoring carried out at one site was two and a half years.

The study reports fourteen main conclusions. In particular, it concluded that in Poland, unconventional gas-bearing formations occur at great depths and are surmounted by deposits that provide excellent sealing capability with regard to potential upward migration of fluids or gas to the main commercial aquifers. Hydraulic fracture stimulation of individual wells did not induce seismic vibrations that are noticeable on the ground surface and recorded vibrations did not exceed the permitted vibration limit values for the stability of structures under Polish law. The noise levels in immediate vicinity of drill sites occasionally exceeded the permitted daytime values for inhabited areas. These exceedances were connected with the operation high-output pumps at some stages of hydraulic fracture stimulation jobs. The operation of some high-power combustion devices can cause a temporary increase in the concentration of gases (fuel combustion products) in the air. Elevated radon concentrations in drilling areas were not observed.

Water usage under relevant water permits at all test sites had no effect on the status of groundwater resources and did not cause a lowering of the groundwater level. The study showed no negative impact of exploration on the ground and surface water chemistry in the observed period of time. There was no contamination of the groundwater as a result of well stimulation, but the obtained results indicate that operations made improperly on the drill site may potentially result in penetration of certain substances from the surface to the top aquifer. However, the reported cases were limited to small areas only.

Drill site operations had no adverse effects on soil quality for farming, but the study concluded that a prolonged load may affect the degree of subsoil compaction, adversely affecting agricultural production until the initial conditions are restored. Drilling operations had a relatively short-term effect on the landscape and should not leave any significant imprint on the landscape upon completion of operations.

In conclusion, the study concluded that operations at the drilling sites may have a potential direct, although limited and short-term, adverse impact on the environment, while stressing the need for "*an adequate control of operations and the establishment of uniform monitoring of the environment (topmost and commercial aquifers, as well as soil gas in immediate drill site vicinity)*". Further, the study stressed that "*Such monitoring must be strictly adapted to the local geological and hydrogeological conditions, should be independent and guarantee reliability and comparability of results*".

5.1.2 New York State Department of Environmental Conservation (2015)

In the state of New York, most projects or activities proposed by a state agency or local government require an environmental impact assessment. Such assessment is prescribed by a State Environmental Quality Review act (SEQR), which requires the governmental body to identify and mitigate the significant environmental impacts of the activity it is proposing or permitting.

The New York State Department of Environmental Conservation released in 2015 the results of the SEQR for high-volume hydraulic fracturing. The review lasted seven years and aimed at evaluating "*the environmental impacts of this activity, determin[ing] the measures and controls that would minimize such impacts, review and understand the science and experiences observed in other parts of the country, and understand the risks and uncertainties arising from the activity.*" It concluded that "*there are no feasible or prudent alternatives that would adequately avoid or minimize adverse environmental impacts and that address the scientific uncertainties and risks to public health from this activity*". Consequently it was decided to officially prohibit high-volume hydraulic fracturing in the state of New York "*based on the balance between protection of the environment and public health and economic and social considerations*".

The study is published in two volumes (New York State Department of Environmental Conservation 2015a; New York State Department of Environmental Conservation 2015b) and the main findings are summarised in a shorted document (New York State Department of Environmental Conservation 2015c).

The assessment's webpage (link in the footnote[6]) include the full suits of accompanying documents and appendixes.

5.1.3 National Energy Technology Laboratory (NETL) (2014)

The National Energy Technology Laboratory commissioned in 2014 a study to survey the state of published descriptions of the potential environmental impacts of unconventional natural gas upstream operations within the lower 48 United States. The goal of the study was to ensure that the predominant concerns about unconventional natural gas development, as covered by current literature, were identified and described. The sources used were publicly available documents, without offering judgment or endorsement of particular results. The following topic were covered: (1) Greenhouse Gas

[6] http://www.dec.ny.gov/energy/75370.html

Emissions and Climate Change, (2) Air Quality, (3) Water Use and Quality, (4) Induced Seismicity, and (5) Land Use and Development. In particular, the latter topic was further subdivided by analyzing (a) property rights and public lands, (b) surface disturbance, (c) cumulative landscape impacts, (d) description and mitigation options for habitat fragmentation impacts, and (e) traffic, noise, and light impacts (NETL 2014).

A discussion is offered regarding greenhouse gas (GHG) emissions released by the natural gas supply chain. The report identifies five major studies that account for the GHG emissions from upstream natural gas, including the construction and completion of gas wells as well as subsequent production, processing, and transport steps. The assumptions and parameters of the five studies vary, but, given their uncertainties, four of the five studies conclude that the GHG emissions from a unit of delivered unconventional natural gas are comparable to (if not lower than) those from a unit of conventional natural gas. The fifth study concludes that the high methane emissions from unconventional well completion and a lack of environmental controls at unconventional extraction sites translates to higher GHG emissions from unconventional natural gas than from conventional natural gas.

The study also focuses on land use and habitat fragmentation. "Although not as extensively documented as other environmental impacts like water quality and greenhouse gas emissions", land use and development impacts that have been discussed in the literature are diverse and include property rights, use of public lands, cumulative landscape impacts, habitat fragmentation, among others. The study also notes that concerns have been expressed with competing uses for public lands, the cumulative impacts of multiple industries (e.g., timber and tourism), and denial of access to areas with active operations. Mitigation options are identified, including adoption of best-practices for site development and restoration, avoidance of sensitive areas, and minimization of disturbed areas.

5.1.4 Pennsylvania Department of Conservation and Natural Resources (2014)

Pennsylvania's Department of Conservation and Natural Resources established in 2010 a shale gas Monitoring Program to monitor, evaluate, and report on the impacts of shale gas development to the state forest system and its stakeholders. The program has the goal to provide objective and credible information to the public and to improve shale gas management efforts[7]. In 2014 it published a comprehensive report that looked at the effects of shale gas activities on Pennsylvania's forests (Pennsylvania Department of Conservation and Natural Resources 2014).

Many so called "Monitoring Values" were assessed, such as infrastructure, flora and fauna, forest health and landscape, invasive species, water, soil, air, incidents, recreation, community engagement, timber, energy and revenue.

5.1.5 Québec's Strategic Environmental Assessment (2014)

The government of Quebec's province commissioned a strategic environmental assessment. The findings of such assessment were published in a report (in the French language) published in 2014 (Bureau d’audiences publiques sur l’environnement 2014). An English translation of the main conclusions is available[8], as well as a whole range of

[7] http://www.dcnr.state.pa.us/forestry/NaturalGas/monitoringreport/index.htm
[8] http://www.bape.gouv.qc.ca/sections/rapports/publications/bape307_Chap13_ENG.pdf

relevant supporting studies[9]. The assessment was carried out by the Bureau d'audiences publiques sur l'environnement.

The inquiry commission noted a lack of evidence showing that shale gas exploration and exploitation using the hydraulic fracturing in the basin of the St. Lawrence Lowlands would be beneficial for Québec. According to the cost-benefit analysis carried out, shale gas operations would not be profitable for the industry and would in addition generate costs for Québec in excess of the benefits they would offer. In other words, the net social value was assessed to be negative.

5.1.6 Germany's Federal Environment Agency (2014)

The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Umwelt Bundesamt) commissioned a study on the environmental impacts of hydraulic fracturing related to the exploration and exploitation of unconventional natural gas, published in the German language (Dannwolf and Heckelsmüller 2014).

This study, carried out by RiskCom, built on an earlier study entitled "Environmental impacts of tracking in the exploration and production of natural gas from unconventional reservoirs - risk assessment, recommendations for further action and evaluation of existing legal provisions and administrative structures", published in 2012 (Federal Environment Agency (Umweltbundesamt) 2012). Open questions from the 2012 study were investigated, and further environmental issues associated with shale gas extraction were addressed. These were:

1. The development of a groundwater monitoring concept;
2. The evaluation of a possible federal tracking chemicals registry;
3. The analysis of environmentally friendly options for flowback disposal;
4. A review of the current state of research on emissions and climate;
5. The investigation of the potential risks of induced seismicity;
6. Identification and assessment of the aspects related to land use and of the impacts on the ecosystem, the landscape and biodiversity.

The goal was to provide a technical and scientific assessment of the risks associated with the above mentioned subjects. The technical and scientific work on the individual topics was based on extensive national and international literature research. In addition to this, interviews were conducted with experts, technical and regulatory authorities, industrial associations and E&P industry representatives.

5.1.7 Environmental Protection Agency of Ireland (ongoing)

In 2011 the Environmental Protection Agency of Ireland was requested by the Irish government to commission and coordinate the management of research in relation to the environmental impacts of unconventional gas exploration and extraction. The EPA established a Steering Committee of relevant stakeholders and held a detailed public consultation in 2013 to inform the terms of reference for such a Research Programme. Funding for the research programme was committed by various governmental departments. In August 2014, the contract to carry out the research was awarded to a consortium led by CDM Smith Ireland Limited.

The research programme was designed to produce outputs that will assist regulators to fulfil their statutory roles regarding impact assessment and regulation of any potential

[9] http://www.bape.gouv.qc.ca/sections/mandats/gaz_de_schiste-enjeux/documents/liste_documents.htm

unconventional hydrocarbons operations in Ireland. The two key questions posed for the research programme were

1. Can unconventional projects and operations be carried out in the island of Ireland whilst also protecting the environment and human health?
2. What is the best environmental practice in relation to unconventional projects and operations?

The research, intended to be completed in two overlapping phases, involves extensive desk-based work (literature review and assessment) by technical experts (Phase 1) as well as baseline-monitoring of seismicity and water resources (Phase 2). At the time of writing, Phase 1 was substantially completed. In January 2016, the EPA was requested by the Department of Communications, Energy and Natural Resources to pause the next Phase of the research to allow time to review the multiple outputs of Phase 1. Following consideration of this request by the project Steering Committee, the Steering Committee has agreed to complete Phase 1 of the study before any decision is made about future work.

An integrated report should be prepared and published later in 2016, along with recommendations for any additional research considered appropriate to address the two key questions posed for the study. See the link provided in the footnote for more details regarding this ongoing project[10].

5.2 Well Integrity

5.2.1 ReFINE study (2014) on well integrity

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 8.3.2 for more information). The consortium published in 2014 a study that assessed all available reliable datasets on well barrier and integrity failure in the published literature and online. Twenty five datasets were studied (Davies, Almond et al. 2014), which included production, injection, idle and abandoned wells, both onshore and offshore, exploiting both conventional and unconventional reservoirs.

The datasets varied considerably in terms of the number of wells examined, their age and their designs, and hence the percentage of wells that showed form of integrity failure was highly variable. The study reported that, among the 8030 wells in the Marcellus shale inspected in Pennsylvania between 2005 and 2013, around 6% had been reported to the authorities for infringements related to well barrier or integrity failure. In a separate study of 3533 Pennsylvanian wells monitored between 2008 and 2011, there were 85 examples of cement or casing failures, 4 blowouts and 2 examples of gas venting. The study also reported that in the UK, 2152 hydrocarbon wells were drilled onshore between 1902 and 2013 mainly targeting conventional reservoirs. Because UK regulations include reclamation of the well site after well abandonment, many wells (around 65%) are not visible anymore from the surface, and hence monitoring is not carried out. The study found that the ownership of more than half the wells is unclear and therefore recommended the importance of establishing appropriate financial and monitoring processes so as to minimize legacy issues associated with the drilling of wells for shale gas and oil.

The study concluded that integrity failure is a reasonably well documented problem for conventional hydrocarbon extraction and the available data showed that it is an important issue for unconventional gas wells as well. Few data exist in the public domain for the failure rates of onshore wells in Europe. It is also unclear which of the datasets

[10] http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee%20research

used in this study are the most appropriate analogues for assessing integrity failure rates at shale gas production sites in the UK and Europe. Only two wells in the UK recorded well integrity failure but this figure is based only on data that were publicly available or accessible to the authors. Therefore, they concluded that the number is likely to be an underestimate of the actual number of wells that have experienced integrity failure.

This study was criticized in a commentary published in the same journal (Thorogood and Younger 2015). According to these authors, (Davies, Almond et al. 2014) failed to acknowledge that well integrity is a product of local regulation, technology and prevailing operational culture, and therefore the search for analogues and the attempt to extrapolate failure rates from a diverse international dataset to the UK situation is not defensible. The ReFINE authors replied to the criticism in (Davies, Almond et al. 2015).

5.3 Water Quality & Use

5.3.1 US EPA (2015) assessment of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources (External review draft)

The United States Environmental Protection Agency (US EPA) released in 2015 a draft assessment of the potential impacts to drinking water resources from hydraulic fracturing for public comment and peer review. The assessment is meant to provide a review and synthesis of available scientific literature and data to assess the potential for hydraulic fracturing for oil and gas to impact the quality or quantity of drinking water resources. Further, it identifies factors affecting the frequency or severity of any potential impacts (US EPA 2015).

The scope of the assessment was defined by the hydraulic fracturing water cycle and includes five main activities:

- *Water acquisition*, i.e. the withdrawal of ground or surface water needed for hydraulic fracturing fluids;
- *Chemical mixing*, i.e. the mixing of water, chemicals, and proppant on the well pad to create the hydraulic fracturing fluid;
- *Well injection*, i.e. the injection of hydraulic fracturing fluids into the well to fracture the geologic formation;
- *Flowback and produced water*, i.e. the return of injected fluid and water produced from the formation to the surface, and subsequent transport for reuse, treatment, or disposal; and
- *Wastewater treatment and waste disposal*, i.e. the reuse, treatment and release, or disposal of wastewater generated at the well pad, including produced water.

The external review draft identified potential mechanisms by which hydraulic fracturing could affect drinking water resources. Above ground mechanisms affecting surface and ground water resources included (1) water withdrawals at times or in locations of low water availability, (2) spills of hydraulic fracturing fluid and chemicals or produced water, and (3) inadequate treatment and discharge of hydraulic fracturing wastewater. Below ground mechanisms included (1) movement of liquids and gases via the production well into underground drinking water resources and (2) movement of liquids and gases from the fracture zone to these resources via pathways in subsurface rock formations.

The external review draft did not find evidence that the mechanisms above have led to widespread, systemic impacts on drinking water resources in the United States. Specific instances were found where one or more of these mechanisms led to impacts on drinking water resources, including contamination of drinking water wells. Such cases occurred during both routine activities and accidents and resulted in impacts to surface or ground water. Spills of hydraulic fracturing fluid and produced water in certain cases reached drinking water resources, both surface and ground water. Discharge of treated hydraulic fracturing waste water were found to have increased contaminant concentrations in receiving surface waters. Below ground movement of fluids were found in some instances to have contaminated drinking water resources. In some cases, hydraulic fracturing fluids were also directly injected into drinking water resources.

Overall, the number of identified cases where drinking water resources were impacted was small relative to the number of hydraulically fractured wells, but the report could not draw a definite explanation. This could reflect a rarity of effects on drinking water resources or may be an underestimate as a result of several factors. The study concluded that "*There is insufficient pre- and post-hydraulic fracturing data on the quality of drinking water resources. This inhibits a determination of the frequency of impacts. Other limiting factors include the presence of other causes of contamination, the short duration of existing studies, and inaccessible information related to hydraulic fracturing activities*".

5.3.2 ReFINE Study (2014) on Radionuclides in Flowback Fluid

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 8.3.2 for more information). The consortium published in 2014 a study that investigated the flux of radioactivity in flowback fluid from shale gas development in three different countries: UK (Bowland Shale), Poland (Silurian Shale) and the USA (Carboniferous Barnett Shale) (Almond, Clancy et al. 2014).

The radioactive flux from these basins was estimated from estimates of the number of wells developed or to be developed, the flowback volume per well and the concentration of potassium radium in the flowback water. The study found that for the Barnett Shale in the USA and the Silurian Shale in Poland, the 1% exceedance flux (i.e. the flux that would only be expected to be exceeded 1% of the time, a reasonable worst case scenario) in flowback water was between seven and eight times that would be expected from local groundwater. However, for the Bowland Shale in the UK, the 1 % exceedance flux in flowback water was 500 times that expected from local groundwater. In any case, in no considered scenario was the 1 % exceedance exposure greater than 1 mSv (the allowable annual exposure allowed for in the UK), and the radioactive flux per unit of energy produced was lower for shale gas than for conventional oil and gas production, nuclear power production and even electricity generated by burning coal.

5.3.3 Ground Water Protection Council (2014)

The Ground Water Protection Council (GWPC) published in 2014 an update to the 2009 publication, "*State Oil and Natural Gas Regulations Designed to Protect Water Resources*" (Ground Water Protection Council 2009). The purpose of the earlier study, based on a review of 27 states, was to describe selected areas and related elements of state oil and gas regulations designed to protect water resources and to generally describe the rule language and state approaches related to those areas.

The update (Ground Water Protection Council 2014) describes the continuous regulatory improvement that states have made during the four years from the first edition.

The report also introduced several emerging issues that merit more detailed consideration in future state regulatory evaluations. With regard to well integrity, for example, these include approaches to analysing stratigraphic containment and potential conduits of fluids from the stimulated zone to protected water. Other significant issues related to groundwater protection include: sampling and analysis of water resources potentially impacted by the oil and gas well drilling, completion, and operation activities; treatment operations and waste stream management related to the use of brackish and/or saline groundwater; the reuse of produced water; and the proper disposal, handling, and exposure limits related to naturally occurring radioactive material (NORM) brought to the surface in produced water and drill cuttings. Finally, the report also highlighted several practices adopted by oil and gas-producing states to enhance transparency, efficiency, and effectiveness in regulatory implementation.

5.3.4 NETL study on fracture growth and fluid migration (2014)

The National Energy technology Laboratory (NETLS) published in 2014 the results of a field study in which the induced fracturing of six horizontal gas wells in the Marcellus Shale was monitored (Hammack, Harbert et al. 2014). The study had two research objectives: (1) to determine the maximum height of fractures created by hydraulic fracturing; and (2) to determine if natural gas or fluids from the hydraulically fractured Marcellus Shale had migrated upward to an overlying Upper Devonian/Lower Mississippian gas field during or after hydraulic fracturing.

The monitoring program included: (1) gas pressure and production histories of three Upper Devonian/Lower Mississippian wells; (2) chemical and isotopic analysis of the gas produced from seven Upper Devonian/Lower Mississippian wells; (3) chemical and isotopic analysis of water produced from five Upper Devonian/Lower Mississippian wells; and (4) monitoring for perfluorocarbon tracers in gas produced from two Upper Devonian/Lower Mississippian wells. Sampling to detect possible migration of fluid and gas from the underlying hydraulically fractured Marcellus Shale gas wells commenced 2 months prior to hydraulic fracturing to establish baseline conditions. Analyses were completed for gas samples collected up to 8 months after hydraulic fracturing and for produced water samples collected up to 5 months after hydraulic fracturing. The authors found no evidence of gas migration nor brine migration from the Marcellus Shale during the monitored period after hydraulic fracturing.

5.3.5 Peer-reviewed journal articles

(Jackson, Lowry et al. 2015) is a study the goal of which was to quantify the depths of recent hydraulic fracturing in the Unites States and to analyze the water used for hydraulic fracturing. Using ~44 000 observations of hydraulic fracturing depths reported to FracFocus between 2008 and 2013, the authors addressed three questions: (1) the range of depths and water use for hydraulic fracturing across the United States; (2) in which states and at what locations the shallowest high-volume hydraulic fracturing occurred; and (3) what policy protections were or might have been put in place to minimize the risk of direct contamination of drinking water from hydraulic fracturing. The study found that some 5% of the wells drilled shallower than one mile (1600m) and about 1% of wells drilled shallower than 3000 ft (914m) were hydraulically fractured in several US states. The analysis suggests that "*additional safeguards would be beneficial if shallow hydraulic fracturing continues in the future", considering that "fractures can propagate 2000 ft (609 m) upward*".

(Kondash and Vengosh 2015) evaluated the overall water footprint of hydraulic fracturing of unconventional shale gas and oil throughout the United States based on integrated data from multiple database sources. It showed that between 2005 and 2014, unconventional shale gas and oil extraction used 708 billion liters and 232 billion liters of water, respectively. From 2012 to 2014, the annual water use rates were 116 billion liters per year for shale gas and 66 billion liters per year for unconventional oil. The authors concluded that while the hydraulic fracturing revolution has increased water use and generated new sources of highly saline and toxic wastewater production in the United States, its water use and produced water intensity, when normalised to the energy production, is not higher than conventional oil or coal mining and represents only a fraction of total industrial water use nationwide.

We additionally mention the following papers published on the topic of water quality and use, although this is not meant to be an exhaustive list:

- "*Impact to Underground Sources of Drinking Water and Domestic Wells from Production Well Stimulation and Completion Practices in the Pavillion, Wyoming, Field* " (DiGiulio and Jackson 2016).
- *Overview of Chronic Oral Toxicity Values for Chemicals Present in Hydraulic Fracturing Fluids*" (Yost, Stanek et al. 2016)
- "*Brine Spills Associated with Unconventional Oil Development in North Dakota*" (Lauer, Harkness et al. 2016).
- "*Water Use and Management in the Bakken Shale Oil Play in North Dakota*" (Horner, Harto et al. 2016).
- "*A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States*" (Vengosh, Jackson et al. 2014).

5.4 Emissions of methane and other greenhouse gasses

5.4.1 ReFINE study on fugitive methane emissions (2016)

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 8.3.2 for more information). The consortium published in 2016 a study that investigated fugitive emissions of methane from former oil and gas exploration and production wells drilled to exploit hydrocarbon reservoirs onshore in the UK (Boothroy, Almond et al. 2016).

This study selected 102 wells which appeared to be properly decommissioned (with ages between 8 and 79 years), located in four different basins. The soil gas above each well was analysed and assessed relative to nearby control sites of similar land use and soil type. The results showed that of the wells considered, 30% had soil gas methane at the soil surface that was significantly greater than their respective control. Conversely, 39% of well sites had significant lower surface soil gas methane concentrations than their respective control. The authors interpret the elevated methane concentrations to be the result of well integrity failure, but could not explain the source of the gas nor the route to the surface. Where elevated methane was detected, it appeared to have occurred within a decade of the well being drilled. The authors also noted that the measured methane fluxes at the wells were actually low relative to the activity commonly used on decommissioned well sites (such as sheep grazing).

5.4.2 University of Austin study on methane emissions (2015)

A team of researchers from the Cockrell School of Engineering at The University of Texas at Austin carried out a study[11] on methane emission, looking at two major sources of methane emissions, liquid unloadings (Allen, Sullivan et al. 2015) and pneumatic controller equipment (Allen, Pacsi et al. 2015), at well pad sites across the United States.

The study found that 19% of the pneumatic devices accounted for 95% of the emissions from pneumatic devices, and 20% of the wells with unloading emissions that vent to the atmosphere accounted for 65% to 83% of those emissions.

[11] http://dept.ceer.utexas.edu/methane2/study/index.cfm

5.4.3 Peer-reviewed journal articles

We mention the following papers on emissions, although this is not meant to be an exhaustive list:

- "*Aerial Surveys of Elevated Hydrocarbon Emissions from Oil and Gas Production Sites*" (Lyon, Alvarez et al. 2016). The authors performed helicopter-based infrared camera surveys of more than 8000 oil and gas well pads in seven U.S. basins to assess the prevalence and distribution of high-emitting hydrocarbon sources. It concluded that "*the proportion of sites with high-emitting sources was 4% nationally but ranged from 1% in Wyoming to 14% in North Dakota. (…) Over 90% of almost 500 detected sources were from tank vents and hatches*"
- "*Reconciling divergent estimates of oil and gas methane emissions*" (Zavala-Araiza, Lyon et al. 2015). In the study the authors tried to reconcile estimates of methane emissions from atmospheric data (top-down approaches) from source-based inventories (bottom-up approaches) based on data from the Barnett Shale. They concluded inter alia that "*two percent of oil and gas facilities in the Barnett accounts for half of methane emissions at any given time, and high-emitting facilities appear to be spatiotemporally variable. Measured oil and gas methane emissions are 90% larger than estimates based on the US Environmental Protection Agency's Greenhouse Gas Inventory and correspond to 1.5% of natural gas production. This rate of methane loss increases the 20-y climate impacts of natural gas consumed in the region by roughly 50%*".
- "*Influence of oil and gas field operations on spatial and temporal distributions of atmospheric non-methane hydrocarbons and their effect on ozone formation in winter*" (Field, Soltis et al. 2015). It found, inter alia, that "*fugitive emissions of natural gas and of condensate were the two principal emission source types for non methane hydrocarbons*".

5.5 Public Health/Environment

5.5.1 The Center for Rural Pennsylvania's study (2015)

The Center for Rural Pennsylvania commissioned an impact study that looked at health and health care as a consequence of shale gas developments in the Marcellus shale (The Center for Rural Pennsylvania 2015).

The motivation behind the study was the uncertainty related to the potential human health effects of Marcellus Shale drilling and related development activities. It was considered likely that different phases of drilling and development may affect human health differently, with some aspects of drilling impacting health directly and others indirectly. The research examined changes in healthcare services, the use of healthcare services, reported injuries, and emergency medical service complaints in four counties in Pennsylvania before and after the start of shale gas developments. The objective was to determine if incidences of certain health status indicators and demand for healthcare services changed in the study counties during the years that Marcellus drilling activity increased. Results indicated that:

- Inpatient hospitalizations in the four counties and the two regions increased slightly in the northern tier and decreased slightly in the southwest, but it was not possible to directly connect this to Marcellus Shale drilling.
- There were no overall trends for injuries in the four study counties. There were noticeable increases in injuries associated with falls and motor vehicle accidents, but these types of injuries could be related to any type of large-scale construction activity and not necessarily to Marcellus Shale drilling.
- There was a substantial increase in the number of emergency medical services complaints, however data was not available on the exact nature of the injuries and

complaints could not be tied directly to drilling activity. A likely relationship was inferred given the time frame in which the data were reported.

- Data should be collected in a more consistent and systematic way to allow for more meaningful analyses.

5.5.2 Pennsylvania Department of Environmental Protection study on TENORMs (2015)

In 2013, the Pennsylvania Department of Environmental Protection initiated a study to collect data relating to technologically enhanced naturally occurring radioactive materials (TENORMs) associated with oil and gas operations in Pennsylvania. This study included the assessment of potential worker and public radiation exposure, TENORM disposal, and other possible environmental impacts. The study encompassed radiological surveys at well sites, wastewater treatment plants, landfills, gas distribution and end use, and O&G brine-treated roads. The media sampled included solids, liquids, natural gas, ambient air, and surface radioactivity. The final report was published in 2015 (Pennsylvania Department of Environmental Protection 2015).

The following conclusions were drawn:

1. There is little potential for additional radon exposure to the public due to the use of natural gas extracted from geologic formations located in Pennsylvania.
2. There is little or limited potential for radiation exposure to workers and the public from the development, completion, production, transmission, processing, storage, and end use of natural gas. There are, however, potential radiological environmental impacts from fluids if spilled.
3. There is little potential for radiation exposure to workers and the public at facilities that treat wastes. However, there are potential radiological environmental impacts that should be studied at all facilities treating wastes to determine if any areas require remediation.
4. There is little potential for radiation exposure to workers and the public from landfills receiving waste from the oil and gas industry. However, filter cake from facilities treating oil and gas wastes are a potential radiological environmental impact if spilled, and there is also a potential long-term disposal issue.
5. While limited potential was found for radiation exposure to recreationists using roads treated with brine from conventional natural gas wells, further study of radiological environmental impacts from the use of brine from the oil and gas industry for dust suppression and road stabilization should be conducted.

5.5.3 British Columbia's Ministry of Health study (2015)

The Ministry of Health (MoH) funded an assessment of the human health risks associated with oil and gas activities in northeastern British Columbia. The study was carried out by a consortium of companies led by Intrinsik (Intrinsik Environmental Sciences Inc. 2014).

The objectives of this study were to provide a comprehensive and focused assessment of potential health risks that may exist for people living in proximity to oil and gas activities.

The literature review conducted concluded inter alia that "*there is an apparent need for additional studies with case control or cohort study designs to evaluate the potential association between cancer incidence and oil and gas activity*", and that "*there is an overall lack of published research regarding respiratory health effects and oil and gas activities*" and "*the majority of the studies evaluated lacked information regarding* *exposure pathways of interest, exposure concentrations, or chemicals of potential concern*".

The risk assessment (which had a regional focus) found that, in general, the predicted short-term air concentrations of chemicals of potential concern were less than their health based exposure limits. Also, the potential combined risks of these chemicals were not predicted to result in adverse health effects in people living or visiting the study area. However, the predicted exposures at some locations were found to exceed exposure limits for certain individual chemicals (such as acrolein, formaldehyde, NO_2 and SO_2). The exceedances for formaldehyde, NO_2 and SO_2 were found to be attributable to oil and gas emission sources, with some contributions from other sources in the area. Overall, long-term inhalation exposures to the chemicals of potential concern were predicted to be associated with a low potential for adverse health effects. The overall findings of the detailed assessment suggested that, while there is some possibility for elevated chemical concentrations to occur at some sites, the probability that adverse health impacts would occur in association with these exposures is considered to be low. It is to be noted that "aerial deposition onto regional water bodies, direct releases to water (groundwater or surface water) were not included in the detailed human health risk assessment".

The report makes a range of recommendations including inter alia the need to update land-use and setback provisions, to implement baseline, pre-drilling ground water testing requirements (with results to be made publically available), to refine its fracturing fluid disclosure process, to pursue air monitoring and to expand the aquifer mapping.

5.5.4 Quebec National Public Health Institute (2015)

As part of Québec's Strategic Environmental Assessment (see also Section 5.1.5), or SEA, and more specifically contributing to the work carried out under the Human Health and Safety component of the SEA working group on health and societal impacts, the Institut National de Santé Publique du Québec (Quebec National Public Health Institute) was given the mandate to document the issues and potential effects on public health related to the exploration and production of gas and oil hydrocarbons.

The following objectives were specified: (1) draw up a knowledge profile on potential risks for human health (both in the general population and the workers) related to gas and oil hydrocarbon exploration and production; (2) determine the additional knowledge required on public health and hydrocarbon exploration and production activities; and (3) propose prevention and management options regarding the health risks that the public might be exposed to in relation to hydrocarbon exploration and production in Quebec.

The study was published in 2015 (Quebec National Public Health Institute 2015).

5.5.5 New York State Department of Health (2014)

In 2012, the New York State Department of Environmental Conservation requested that the Department of Health (DOH) to review and assess its analysis of potential health impacts contained in DEC’s draft supplemental generic environmental impact statement (SGEIS) for high-volume hydraulic fracturing (see Section 5.1.2). In response, DOH initiated a Public Health Review process.

In conducting this public health review DOH: (1) reviewed and evaluated scientific literature to determine whether the current scientific research is sufficient to inform questions regarding public health impacts of high-volume hydraulic fracturing; (2) sought input from outside public health expert consultants; (3) engaged in field visits and discussions with health and environmental authorities in US states where shale gas extraction is taking place; and (4) communicated with multiple stakeholders (local, state, federal, international, academic, environmental, and public health bodies).

The evaluation considered the available information on potential pathways that connect high-volume hydraulic fracturing activities and environmental impacts to human exposure and the risk for adverse public health impacts. The study was published in 2014 (New York State Department of Health 2014).

The report noted that while a guarantee of absolute safety is not possible, an assessment of the risk to public health must be supported by adequate scientific information to determine with confidence that the overall risk is sufficiently low to justify proceeding with high-volume hydraulic fracturing in the state of New York. The report concluded that current scientific information is insufficient and that, furthermore, existing literature and experience show that high-volume hydraulic fracturing activities have resulted in environmental impacts that are potentially adverse to public health.

The report recommended that, until the science can provide sufficient information to determine the level of risk to public health and whether the risks can be adequately managed, high-volume hydraulic fracturing should not take place in the state of New York.

5.5.6 Peer-reviewed journal articles

A list of peer-reviewed papers can be found on the website of the TEDX (The Endocrine Disruption Exchange), an organization focusing primarily on the human health and environmental problems caused by low-dose and ambient exposure to chemicals[12]. We herein mention the following papers on public health, although this is not meant to be an exhaustive list:

- "*Toward an Understanding of the Environmental and Public Health Impacts of Unconventional Natural Gas Development: A Categorical Assessment of the Peer-Reviewed Scientific Literature, 2009-2015*" (Hays and Shonkoff 2016).
- "*Public Health, Risk Perception, and Risk Communication: Unconventional Shale Gas in the United States and the European Union*" (Goldstein, Renn et al. 2016).
- "*Atmospheric Emission Characterization of Marcellus Shale Natural Gas Development Sites*" (Goetz, Floerchinger et al. 2015).
- "*Predictors of indoor radon concentrations in Pennsylvania, 1989-2013*" (Casey, Ogburn et al. 2015).
- "*Perinatal Outcomes and Unconventional Natural Gas Operations in Southwest Pennsylvania*" (Stacy, Brink et al. 2015).
- "*Environmental health impacts of unconventional natural gas development: A review of the current strength of evidence*" (Werner, Vink et al. 2015).
- "*Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development*" (Adgate, Goldstein et al. 2014).
- "*Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region*" (Ferrar, Kriesky et al. 2013).
- "*The implications of unconventional drilling for natural gas: a global public health concern*" (Finkel and Hays 2013).

[12] http://www.endocrinedisruption.org/chemicals-in-natural-gas-operations/peer-reviewed-articles

5.6 Seismicity

5.6.1 Central Mining Institute of Katowice (2015)

A seismic monitoring study of Polish drilling sites was commissioned by the Polish ministry of the environment and carried out by the Central Mining Institute in Katowice.

The aim of the project was to design and installed networks of seismic probes to measure the seismic vibrations in three areas where hydraulic fracturing treatments were carried out. These were the Syczyn-OU2K well in Syczyn and the Zwierzyniec-1 well in Zawada (both in the Lubelskie Voivodeship) and the Gapowo-1 well in Stężyca (in the Pomorskie Voivodeship). The final report was published in 2015 (Lurka, Mutke et al. 2015).

The purpose of the seismic networks was to carry out continuous digital recording of seismic background and seismic events in designated areas around the wells. Specifically, the task of seismometers was to register vibrations caused by work carried out in the wells. Seismic monitoring included the following works: preparation: determination of the installation sites, installation of equipment, seismic background measurement before hydraulic fracturing, measurement during hydraulic fracturing, and measurement after hydraulic fracturing.

The study concluded that registered vibrations did not exceed the permissible vibration levels according to the Polish standard (PN-88 / B-02171) and had no impact on people in buildings.

5.6.2 Peer-reviewed journal articles

We mention the following papers on induced seismicity, with a particular focus on the European situation, although this is not meant to be an exhaustive list:

- From the ReFine Project: "*Anthropogenic earthquakes in the UK: A national baseline prior to shale exploitation*" (Wilson, Davies et al. 2015). In this study the authors reviewed the distribution, timing and probable causes of ~8000 onshore UK seismic events between the years 1970-2012.
- From the ReFine Project: "*Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons*" (Davies, Foulger et al. 2013). In this study the authors compiled published examples of induced earthquakes with magnitudes ≥ 1.0 that have occurred in the UK since 1929.
- From the U.S. Geological Survey and the Geological Survey of Canada: "*Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity*" (Rubinstein and Mahani 2015). In this paper, induced seismicity associated with wastewater injection and hydraulic fracturing is discussed.
- "*Hydraulic Fracturing and Seismicity in the Western Canada Sedimentary Basin*" (Atkinson, Eaton et al. 2016). The authors notably concluded that whilst in the central United States, most induced seismicity is linked to deep disposal of produced waste water from oil and gas extraction, in western Canada most recent cases of induced seismicity are highly correlated in time and space with hydraulic fracturing.

5.7 Chemical additives usage

(Elsner and Hoelzer 2016) attempted to bridge the gap between existing alphabetical disclosures by function and emerging scientific contributions on fate and toxicity of hydraulic fracturing additives. Published in early 2016, the study quantitatively reviewed the structural properties of additives, using voluntary U.S. disclosures from the FracFocus registry and from a House of Representatives database, the so-called "Waxman" list (Waxman, Markey et al. 2011).

The authors noted that out of more than a thousand reported substances, classification by chemistry yielded only small sets where it was possible to illustrate the rationale of their use and properly identify physical and chemical properties relevant for determining environmental fate and toxicity. Whilst many substances were nontoxic, frequent disclosures also included notorious groundwater contaminants such as petroleum hydrocarbons (solvents), precursors of endocrine disruptors, toxic propargyl alcohol, biocides and strong oxidants. Application of highly oxidizing chemicals suggested to the authors the possibility that relevant transformation products may be formed and advocated full disclosure of hydraulic fracturing additives in order to adequately investigate such reactions.

5.8 Surface impacts

5.8.1 ReFINE study (2016) on traffic impacts

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 8.3.2 for more information). The consortium published in 2016 a study that presented an environmental assessment of traffic impacts for individual and groups of hypothetical fracking sites (Goodman, Galatioto et al. 2016). In this study, a model was developed to produce estimates of the traffic-related impacts of fracking on greenhouse gas emissions, local air quality emissions, noise and road pavement wear, using a range of hypothetical scenarios to quantify changes in impacts against baseline levels.

Results suggested that the local impacts of a single well pad may be of short duration but of large magnitude. For instance, the model showed that whilst small percentage increases in emissions of CO_2, NO_x and particulate matter were estimated for the period from start of construction to pad completion, excess emissions of NO_x on individual days of peak activity could reach 30% over the baseline values. Similarly, excess noise emissions appeared negligible when normalised over the completion period, but could be considerable in particular hours, especially in night-time periods. The use of the model to explore hypothetical future technology timelines over a range of well development scenarios covering several decades showed that the overall impact to a region, or a country as a whole, appeared "*somewhat negligible compared to general traffic or industrial activities, though it is recognised that the methodology used may underestimate emissions associated with network congestion*".

6 Hydraulic fracturing in the social sciences

There has been a growth in social science research on fracking recently, especially since 2010 (Williams, Macnaghten et al. 2015).This growing body of work has largely focused on three areas: policy research (Rinfret, Cook et al. 2014), attitude surveys (Boudet, Clarke et al. 2014) and fracking in the media (Jaspal and Nerlich 2014).

6.1.1 ReFINE study (2015) on the public perception of hydraulic fracturing

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 8.3.2 for more information). The consortium published in 2015 a study on the public perceptions of hydraulic fracturing. This paper was motivated by an analysis by (Jaspal, Turner et al. 2014), claiming that there is both a lack of research on the public perceptions of hydraulic fracturing and consideration from the point of view of science and technology studies.

The ReFINE study (Williams, Macnaghten et al. 2015) was aimed at addressing both these gaps. In particular, it explored the factors that are shaping the public controversy through qualitative research on public perceptions in the United Kingdom. The UK institutional framing of hydraulic fracturing policy and the understanding of fracking articulated by lay participants, derived from six in-depth qualitative focus groups held in early 2013, were explored.

The authors argued that the problem associated with fracking is not simply about the existence of objective risks, nor just about the ability of the public to understand them, but also about the institutional ability and willingness to recognise and accommodate diverse public views. Four key lessons for policymakers emerged from this research. First, it is important that policymakers avoid adopting the position of salesperson for fracking because salespeople are not likely to be viewed as legitimate arbiters. Second, it is important to submit the possible benefits of fracking to the same level of scrutiny as the risks. Third, policymakers should avoid giving the disingenuous impression that there is no choice on whether to go ahead or not with the exploitation of shale gas. Finally, engagement with the public must be a real dialogue, not a monologue.

7 Risk and safety assessments

7.1 TNO study (2015)

In 2013, a study commissioned by the Dutch government was carried out carry into the possible risks and consequences of the exploration for and extraction of shale and coal gas in the Netherlands (Witteveen+Bos, Arcadis et al. 2013). The following conclusions emerged from this assessment:

- Compared with conventional gas extraction, shale gas extraction has a bigger footprint and there are more industrial activities on each drilling site.
- Methane may be released during various phases of exploration and extraction and due to the intensive logistics, longer drilling and fracking more CO_2 is emitted compared with conventional gas extraction.
- Due to the high pressure injection of fracking fluid in or near an active fault zone, earthquakes may possibly occur during shale gas extraction.
- The fracking fluid consists mainly of water containing proppants and additives (approx. 2%). A number of these additives may be harmful in high concentrations.
- One possible risk of shale gas extraction is the contamination of the groundwater due to the failure of well integrity, migration of fluid or methane directly from the shale or coal stratum either via the well or due to spillages and leaks on the drilling site.

The Witteveen+Bos study concluded that the potential risks for nature, people and the environment are manageable and that the current Dutch legal frameworks offer sufficient options for addressing them. It also recommended the execution of site-specific research with the aim of evaluating for each potential extraction site the effects of shale gas extraction on people, nature and the environment.

Because the Witteveen+Bos mainly looked at the subsurface aspects and only to a lesser extent to the surface effects, a further study was commissioned to TNO, to evaluate the existence and development of new technologies that may reduce the risks of shale gas extraction for people and environment with a focus on ground- and drinking water, emissions, induced seismicity and surface footprint. The central research question that was posed was the following: are there developments and technologies with which the (residual) risks of the extraction of shale gas (drilling, fracking, production of gas, water and drilling muds) can be reduced?

TNO published the findings of such study in 2015 in a report titled "*Inventory of technologies and developments for reducing (residual) risks in shale gas extraction*" (Heege, Griffioen et al. 2014). The work included firstly a study of relevant literature, available expert reports and identification of gaps. These gaps were then filled in by interviews with experts and additional literature research. A second phase followed with a process of knowledge integration to answer the research questions posed and to indicate any existing relationship between them.

8 R&D initiatives

Several research projects on unconventional fossil fuels are currently under way both in Europe and worldwide. Four EU-funded projects within the Horizon2020 framework have kicked off and are described in Section 8.1 below. Other EU initiatives are described in Section 8.2. Relevant projects in EU member states are described in Section 8.3. Finally, Section 8.4 reviews several projects taking place in non-EU countries.

The near totality of the projects reviewed is concerned with assessing the environmental risks associated with shale gas exploration and exploitation. The following broad topic areas of research can be identified: (1). Scale and nature of unconventional oil and gas resources in a given region; (2). Water quality and availability; (3). Air quality and greenhouse gas emissions; (4). Effects on human health; (5) Ecological effects; (6) Induced Seismicity.

8.1 EU-funded projects

8.1.1 M4ShaleGas

The M4ShaleGas[13] (Measuring, monitoring, mitigating managing the environmental impact of shale gas) program focuses on reviewing and improving existing best practices and innovative technologies for measuring, monitoring, mitigating and managing the environmental impact of shale gas exploration and exploitation in Europe. The technical and social research activities intend to deliver scientific recommendations on (1) how to minimize environmental risks to the subsurface, surface and atmosphere; (2) how to reduce and mitigate the risk and 3) how to address the public attitude towards shale gas development. Knowledge and experience on best practices will be informed by direct collaboration with US and Canadian research partners and input from representatives from the industry.

8.1.2 SHEER

The objective of SHEER[14] (SHale gas Exploration and Exploitation induced Risks) is to develop best practices for assessing and mitigating the environmental footprint of shale gas exploration and exploitation. The consortium includes partners from Italy, United Kingdom, Poland, Germany, the Netherlands and USA. It intends to develop a probabilistic procedure for assessing short and long-term risks associated with groundwater contamination, air pollution and induced seismicity. The consortium intends to approach the issue from a multi-hazard, multi parameter perspective, by developing methodologies and procedures to track and model fracture evolution around shale gas exploitation sites and a robust statistically based, multi-parameter methodology to assess environmental impacts and risks across the operational lifecycle of shale gas. The developed methodologies will be applied and tested on a comprehensive database consisting of seismicity, changes of the quality of ground-waters and air, ground deformations, and operational data collected from past case studies. Additionally, they will be improved by the high quality data SHEER will collect monitoring micro-seismicity, air and groundwater quality and ground deformation in a planned hydraulic fracturing to be carried out by the Polish Oil and Gas Company in Pomerania.

[13] http://cordis.europa.eu/project/rcn/193743_de.html
[14] http://www.sheerproject.eu/objective.html.

8.1.3 ShaleXenvironmenT

The primary objective of this project[15] is to assess the environmental footprint of shale gas exploitation in Europe in terms of water usage and contamination, induced seismicity, and fugitive emissions. Using both experiments and modeling, this project intend to achieve a much improved understanding of rock-fluid interactions, fluid transport, and fracture initiation and propagation, via technological innovations obtained in collaboration with industry, and via improvements on characterization tools. ShaleXenvironmenT will maintain a transparent discussion with all stakeholders, including the public, and will suggest ideas for approaches on managing shale gas exploitation, impacts and risks in Europe, and eventually worldwide.

8.1.4 FracRisk

The objective of FracRisk[16] is to develop knowledge for understanding, preventing and mitigating the potential impact of the exploration and exploitation through hydraulic fracturing (fracking) of shale gas reserves found throughout Europe, and to develop a decision support tool for risk quantification of the environmental impacts of the technology. The aim is to provide key scientific-based recommendations aimed at minimising the environmental footprint of shale gas extraction through effective planning and regulation, whilst at the same time addressing public concerns.

8.1.5 ShaleSafe

The objective of ShaleSafe is to develop a monitoring system embedded in a sonic drilling pipe for inspection of soil and aquifer contamination by shale gas and hydraulic fracturing chemicals. This project was selected in 2015 for funding under the Fast track to innovation H2020 call.

8.2 EU initiatives

8.2.1 EERA Joint Program on Shale Gas

The European Educational Research Association[17] (EERA) Joint Program on Shale Gas is meant to establish a common knowledge platform for research on the potential, impact and safety of shale gas development in Europe. Existing technologies and methodologies are to be evaluated and improved to establish an independent knowledge basis which is based on research by twenty four independent research institutes from 15 European member states.

8.2.2 UH Network

The European Science and Technology Network on Unconventional Hydrocarbon Extraction[18] (UH Network) was officially established by the 2014 Communication from the Commission on the exploration and production of hydrocarbons (COM/2014/023 final/2). The main objective of the Network, managed by the Joint Research Centre in close cooperation with DG Environment, DG Energy, DG Research & Innovation, DG Climate Action and DG Internal Market, Industry, Entrepreneurship and SMEs, was to collect, analyse and review results from exploration projects as well as to assess the

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[15] https://shalexenvironment.wordpress.com/.
[16] http://www.fracrisk.eu/
[17] http://eera-shalegas.eu/
[18] https://ec.europa.eu/jrc/uh-network

development of technologies used in unconventional gas and oil projects. The objectives of the Network were (1) to structure the dialogue among the stakeholders, fostering open information and knowledge sharing; (2) to present and discuss research activities and their results; (3) to identify research gaps and innovation needs; (4) to examine knowledge gained from exploration and production projects; and (5) to identify and assess emerging technologies including their economic, environment and climate impacts.

Work was organised in two Working Groups. Working group 1 (Exploration, demonstration and production projects in the EU) was tasked with collecting data obtained from exploration and possible demonstration and production projects as well as related research projects carried out in the EU, with the aim to carry out a comparative assessment. Working group 2 (Emerging technologies for well simulation) was tasked to complement and update the JRC document of 2013 providing "an overview of hydraulic fracturing and other formation stimulation technologies for shale gas production" (Gandossi 2013), based on practical experience with these technologies in exploration, possible demonstration and production projects in and outside the EU. The Working Groups carried out their activities in 2015 and were closed at the beginning of 2016. The Network's activities were paused at the Annual conference held in February 2016.

8.3 National Projects and Initiatives in EU Member States

8.3.1 Poland

Blue Gas– Polish Shale Gas

This national programme[19] is a joint undertaking of National Centre for Research and Development (NCBR) and Industrial Development Agency (ARP S.A.). It is focused on supporting integrated large R&D projects, testing results in pilot scale and commercialization of innovative technologies in the area of shale gas extraction. The main aim is the development of technologies related to shale gas extraction in Poland and their implementation by companies operating in Poland.

8.3.2 United Kingdom

Scottish Government

The Scottish Government is conducting a program of research and public consultation for onshore unconventional oil and gas. The detailed evidence-gathering phase will take place between 2015 and 2016 and a consultation phase, covering engagement, public consultation and analysis, is due to conclude in spring 2017. For more information, please refer to the link provided in the footnote[20].

Energy Security and Innovation Observing System for the Subsurface (ESIOS)

This is a programme[21] coordinated by the British Geological Survey (BGS) with the aim of establishing the Energy Security and Innovation Observing System for the Subsurface (ESIOS). ESIOS intends to be a group of science research facilities where subsurface activities such as fracking for shale gas can be tested and monitored under controlled conditions. The scientific data will be published freely online to encourage transparency

[19] http://www.ncbir.pl/en/domestic-programmes/blue-gas-polish-shale-gas
[20] http://www.sepa.org.uk/environment/energy/non-renewable/shale-gas-and-coal-bed-methane/
[21] http://www.bgs.ac.uk/research/energy/shaleGas/esios.html

in the industry and to provide science for regulation. Research will address many of the environmental issues that need to be answered for the development of secure energy solutions, including carbon capture and storage, geothermal energy, nuclear waste disposal, underground coal gasification and underground gas storage. The first ESIOS facility will be based in Thornton, Cheshire and a second site will be located in a suitable area in the UK covering a different range of geological and energy conditions. The new facilities will complement and build on those already at the disposal of the BGS and the wider academic community.

British Geological Survey: Shale gas environmental monitoring

The British Geological Survey (BGS) is monitoring environmental baseline conditions in relation to potential shale gas development in the UK[22]. Monitoring addresses quality of groundwater and surface water, seismicity, atmospheric composition assessment, ground motion (subsidence and uplift). In particular, environmental baseline monitoring is to be undertaken in the Vale of Pickering and in Lancashire by a consortium of universities.

ReFINE

ReFINE[23] (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University. Launched in 2013, ReFINE was formed after trans-European discussions between scientists, policy-makers and the petroleum industry identified the need for unbiased research into shale gas exploitation. The consortium has recently published several studies related to various aspects of hydraulic fracturing, see for instance Sections 5.2.1, 5.3.2, 5.4.1, 5.6.2, 5.8.1 and 6.1.1.

Task Force on Shale Gas

The Task Force on Shale Gas[24] was launched in September 2014 to provide an impartial, transparent and evidence-based assessment of the potential benefits and risks of shale gas extraction to the United Kingdom. The Task Force's funding comes from businesses involved in the shale gas industry. However, the Task Force operates independently from its funders and the funders have no influence over its research, recommendations or publications.

Recognising that the issue of shale gas extraction and its potential benefits and risks is a polarising topic in the UK, the Task Force intended to create a platform to provide reasoned and evidence-based conclusions and recommendations to both industry and Government about the potential of shale gas extraction in the UK, to inform the general public and to promote reasonable discussion about these findings.

A first interim report, published in March 2015, examined the existing planning and regulatory system for shale gas and the public consultation process and made a series of recommendations to address the concerns raised by the public around potential shale gas extraction (Task Force on Shale Gas 2015a).

A second interim report, published in July 2015, looked at the impacts of shale gas associated with the local environment. Specifically it looked at seismic activity, at potential impacts on air and water and on public health impacts. The report made a series of recommendations that would provide a framework under which it would be

[22] http://www.bgs.ac.uk/research/groundwater/shalegas/faq.html
[23] http://www.refine.org.uk/
[24] https://www.taskforceonshalegas.uk

possible to minimise the risk associated with shale gas to acceptable levels (Task Force on Shale Gas 2015b).

A third interim report, published in September 2015, examined evidence related to the potential climate change impacts associated with shale gas. This report concludes that, provided it is firmly regulated, shale gas can contribute to the decarbonisation of the British economy (Task Force on Shale Gas 2015c).

A fourth report, published at the end of 2015, examined the economics of a shale gas industry in the UK, including community benefits and compensation (Task Force on Shale Gas 2015d).

A final set of conclusions was published in early 2016 (Task Force on Shale Gas 2016). A selection of which is reproduced below:

- Shale gas can be produced safely and usefully in the UK provided that the Government insists on industry-leading standards.
- The risk from shale gas to the local environment or to public health is no greater than that associated with comparable industries provided, as with all industrial works, that operators follow best-practice.
- Baseline monitoring is essential to reassure local populations. Monitoring of air, land and water should begin as soon as a site has been identified.
- Operators must be held to the very highest standards for well integrity, which includes independent monitoring.
- The process of “green completions”, recently made compulsory in the US, should also be mandated in the UK for production wells.
- A successful shale gas industry in the UK has the potential to create thousands of jobs directly and support a wider supply chain indirectly.
- Shale gas operations will have an impact, in terms of noise, disruption and traffic, on those communities directly affected by production sites. Operators must do everything possible, and be transparent, in seeking to minimise the effects that their works will have on nearby residents.
- Transparency must be placed at the heart of any nascent shale gas industry. Operators must agree to full disclosure of the chemical content of materials used in shale gas exploration and production and agree that the specific composition will not exceed levels mandated by the Environment Agency.
- Local residents should have a direct role in monitoring any operations in their area. Monitoring of sites is essential.
- The Government must commit to ensuring that the regulatory system for the shale gas industry is robust and fully resourced.
- Gas is required as part of the UK’s energy mix for the short and medium term. It is simply not feasible to create a renewables industry that can meet all our energy needs in the short term. Gas represents an environmentally cleaner alternative to coal, provided methane does not leak during the extraction and transportation of gas. "*If a shale gas industry begins to develop at scale, CCS will become essential, and a CCS industry should be developed and grown concurrently*".
- The emergence of a shale gas industry must not be allowed to restrict or prohibit the ongoing development of a renewables and low-carbon energy industry to meet the United Kingdom’s long-term energy needs.

8.3.3 Germany

Nicht-konventionelle Kohlenwasserstoffe (NiKo)

This project[25] aims at evaluating of the shale gas potential in Germany, conducted by the German Federal Institute for Geosciences and Natural Resources (BGR).

8.3.4 Ireland

As described in greater detail in Section 5.1.7, the Environmental Protection Agency of Ireland is funding an ongoing research effort in relation to the environmental impacts of unconventional gas exploration and extraction.

8.3.5 The Netherlands

In reaction to the public debate on shale, the Dutch Ministry of Economic Affairs set out a study in 2011, on the possible risks and effects of exploration and exploitation of shale gas, which was carried out by Witteveen and Bos, Arcadis and Fugro (Witteveen+Bos, Arcadis et al. 2013). This was described in greater detail in Section 7.1. The resulting advice was that more research is needed to determine the local effects on people and nature, and that environment location-specific investigations are needed, for instance in the form of an environmental impact assessment.

In reaction to this study, the Ministry of Economic Affairs and Infrastructure and Environment decided to develop a "Structural Vision" on shale gas that will give the government information on whether shale gas in the Netherlands could be developed and how and in what areas on national level this could take place. In July 2015 three studies that are part of this initiative were published[26]:

- PlanMER (Environmental impact assessment),
- Inventory of innovative technologies to minimize environmental impact of shale gas development and
- Exploration of societal effects.

Based on the studies above, the Minister announced that no commercial shale gas development will take place in the Netherlands in the next 5 years.

8.4 Important Projects of Major non-EU Countries.

8.4.1 USA

The USA has developed a federal multiagency strategy for coordinating on-going and future research associated with the safe development of onshore shale gas, tight gas, shale oil, and tight oil resources (U.S. DEPARTMENT OF ENERGY, U.S. DEPARTMENT OF THE INTERIOR et al. 2014). This identifies key questions the agencies involved, the Department of Energy (DOE); Department of the Interior (DOI) and the Environmental Protection Agency (EPA) use to guide on-going research[27]. The following describes more in detail some of the initiatives.

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[25] https://www.bgr.bund.de/DE/Themen/Energie/Projekte/laufend/NIKO
[26] http://www.rijksoverheid.nl/documenten-en-publicaties/kamerstukken/2015/07/10/kamerbrief-schaliegas.html
[27] http://unconventional.energy.gov

Marcellus Shale Energy and Environmental Laboratory (MSEEL)

The Department of Energy's National Energy Technology Laboratory (NETL) and several partners conduct this project[28] to monitor the process and progress of unconventional gas production at a Marcellus Shale well near Morgantown, WV. MSEEL will enable continuous monitoring of produced water and air quality. The project also gives researchers access to a dedicated science well for subsurface geophysical observation while NNE deploys a range of next-generation well-completion technologies designed to increase operational efficiency and reduce environmental impact.

EPA's Study of Hydraulic Fracturing for Oil and Gas and Its Potential Impact on Drinking Water Resources

The overall purpose of this study[29], conducted by the U.S. Environmental Protection Agency (EPA), is to investigate how hydraulic fracturing may have an effect on drinking water resources. An external review draft was published in June 2015 for public comments and peer review.

AirWaterGas

The mission of this Sustainability Research Network[30], funded by the National Science Foundation, is to provide a logical, science- based framework for evaluating the environmental, economic, and social trade-offs between development of natural gas resources and protection of water and air resources and to convey the results of these evaluations to the public in a way that improves the development of policies and regulations governing natural gas and oil development.

USGS - Produced Waters

Researchers of the U.S. Geological Survey (USGS) Energy Resources Program (ERP) are engaged in examining several aspects related to characterization, use, and impact of produced waters[31]. Currently research is focused in three areas: (1) the assessment of the impact of coalbed methane produced waters; (2) chemical characterization and sources of Appalachian Basin produced waters; and (3) water balances for energy resource production (water budget methods for understanding water inputs and outputs).

USGS - Hydraulic Fracturing

Research on hydraulic fracturing is underway by a number of USGS offices including the Energy Resources Program, Water Resources, Natural Hazards and Environmental Health[32]. This includes the major environmental study conducted by the U.S. Environmental Protection Agency, mentioned above.

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[28] http://mseel.org
[29] http://www2.epa.gov/hfstudy
[30] http://airwatergas.org
[31] http://energy.usgs.gov/EnvironmentalAspects
[32] http://energy.usgs.gov/OilGas/UnconventionalOilGas

9 Conclusion

The last few years have witnessed a wealth of studies, reports and assessments being published in many EU member states, by national and international organisations and in the research community, covering many aspects related to the exploitation of unconventional hydrocarbons, most notably shale gas. Many R&D initiatives are also underway.

This report has attempted to provide a survey of several of such studies and initiatives, with a focus on shale gas and mainly covering the years 2014, 2015 and early 2016. Some earlier studies (not older than 2011) were covered as well. Principally, reports and studies from public bodies and scientific institutes were included, as well as several papers published in peer-reviewed journals.

Each study or report was briefly described and a selection of its conclusions and/or recommendations, when relevant, was extracted and reproduced herein, but a review of the quality of the studies covered, the accuracy of their claims and their possible limitations was beyond the scope of this report. Therefore, this report is only meant to provide a compilation of such studies and their summaries, without any endorsement of the findings reported.

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